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The Void Specification

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Summary

The purpose of this memo is to explore more fully the allowable void specification, in part to make it clearer to those doing the day-to-day evaluation and in part to help me understand the ramifications. A simulation of voids in a Be shell is used to support my understanding of Haan's analysis. The key results showing allowable void diameter as a function of void fraction are shown in Figure 6 (p. 8). What is important here is that generally in "good" samples we only see small voids, perhaps at most a few tenths of a μm in size. For this void size the shells can be underdense by as much as 10% and still meet the 1 part in 10^4 spec (though there may be other issues with reduced density).

Introduction

The basic specification for uniformity is the nominal 1 part in 10^4 over length scales of 100 μm (about mode 60) for *all* causes of opacity variations. Ultimately Rich Stephens' precision radiography will measure shell opacity, but it is valuable to develop some simpler screening characterization, particularly for voids, at this time to guide fabrication. In his JASON's talk[1] Steve Haan stated a void spec as 1% void fraction with volume of individual voids less than 2 μm^3, though clearly there is a trade off between void fraction and size. Part of the purpose of this memo is to quantify this trade off.

What characterization do we have now? We can measure the density of a full thickness Be shell with an uncertainty of (at best) 1%.[2] The accuracy is largely controlled by the measure of wall thickness, and this is affected by both the absolute thickness and the roughness of the capsule. At this point all of the measurements made at LLNL show at least a 2% void fraction (thus with uncertainties this *might* be as low as 1%), but most of the coatings are much more underdense. We know in part the reason for this and have experiments planned to test methods of making more fully dense coatings. My point here, however, is that the best we can expect for a density measurement on full shells is about 1%. The situation with voids is worse. Some information (qualitative at best) about grain size and microstructure can be learned

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[1] Steve Haan, "Target Design and Implosions," presented to the JASON panel on NIF Ignition, March 25, 2005.

[2] Bob Cook, "Density Measurements of Be Shells," LLNL technical memo, February 14, 2005. A related memo is Bob Cook, Be Shell Wall Thickness by SEM Analysis," LLNL technical memo, March 1, 2005. Copies available from Bob Cook.

from a simple fracture cross-section. Determination of void size and/or distribution requires that FIB samples be prepared for TEM analysis. But these samples are only 10 µm squares, and thus unless lots (10's?) are prepared it is at best a guess based on their analysis what the void size/distribution in the shell is. This is particularly true for a nearly fully dense sample where the number/size of voids may be small. However it is at present the best we can do, and is useful as a screening tool.

Model and calculations

What I want to do in the remainder of this memo is provide some meat, both in terms of understanding (at least mine) and useful numbers, to the void specification. Let me do this in terms of a uniformity criterion. What I will focus on is the expected rms of a series of measurements relative to the mean. Rich Stephens will make a series of measurements of opacity on a shell using an x-ray spot size of about 100 µm. It is reasonable to assume that the voids are randomly scattered, thus the opacity measurement *due to voids alone* will be independent about some mean. To measure the variation in opacity, I'll define ρ_{M} to be the rms of a series of opacity measurements (as will be clearer below I am thinking of density measurements) relative to their mean, expressed in "parts per 10^4," or

$$\rho_{\mathrm{M}} = \frac{\sqrt{\sum_i \left(\langle\rho\rangle - \rho_i\right)^2}}{\langle\rho\rangle} \times 10^4 \qquad (1)$$

where ρ_i is an individual opacity measurement and $\langle\rho\rangle$ is their average. The dependence of ρ_{M} on void fraction and void size is given by

$$\rho_{\mathrm{M}} = C(\text{spot size}) \cdot v_f^{1/2} \cdot d^{3/2} \qquad (2)$$

where the void fraction, v_f, is given by

$$v_f = 1 - \frac{\rho}{\rho_0}\ , \qquad (3)$$

ρ and ρ_0 being the actual and full densities of the material, and d is the diameter of the void (I'll assume sphericity). The easiest way (at least for me) to think of the dependencies in eq 2 is that for a random system the variations go as $N^{1/2}$, where N is the number of the perturbing objects. Thus if we double the void fraction (at constant void diameter) we double the number of voids, thus the dependence on ρ_{M} goes as $v_f^{1/2}$. The situation with void size is a little more complicated. If one simply doubled the size of all voids, then the measure of the rms would simply double. However if one holds the void fraction constant one can only double the volume of the voids by cutting

their number in half. Thus, in net, doubling the volume of the voids doubles ρ_M but reducing the number of voids by a factor of two reduces ρ_M by a factor of $\sqrt{2}$, so the dependence on ρ_M due to void size goes as the square root of void volume or $d^{3/2}$ where d is the more directly measured void diameter.

In order to check this reasoning I modeled the system as follows. I started with a shell that has a diameter, D, of 2000 µm and a wall thickness, w, of 162 µm, essentially the 1 MJ Be design dimensions. Then as input I set the void fraction, v_f, equal to a specific value (between 0.01 and 0.10) and the void diameter, d, to a specific value between 0.1 µm and 10 µm. From these two values I calculated the number, n, of voids that would be in the shell:

$$n = \frac{v_f \cdot V_{\text{shell}}}{V_{\text{void}}} \tag{4}$$

where

$$V_{\text{shell}} = (4/3)\pi\left((D/2)^3 - (D/2 - w)^3\right) \tag{5}$$

is the volume of the shell and

$$V_{\text{void}} = (4/3)\pi(d/2)^3 \tag{6}$$

is the volume of a void, which I assume is spherical. In order to model the measurement, I pick a "spot size" by selecting an angle φ_{spot} over which I am going to simulate an opacity measurement. For example, 6° represents 1/60 th of the circumference or about 105 µm. Thus I will model 60 opacity measurements about the sphere with "spots" that are 6° on a side (sort of square spots on the surface of the sphere). The measurement I will model is for one wall only, the actual measurement (Rich's precision radiography) will by necessity measure two walls simultaneously. The measurement value will be determined by how many voids are placed in each measurement volume when the n voids are placed randomly over the sphere. As a simple measurement value I compute the density of the sample (each square spot) assuming full density, ρ_0, is 1.85 g/cm^3, the density of void free Be. I do this by simply multiplying the number of voids, n_i placed in a wall section times the volume of a void, V_{void}, to determine the amount of "empty" space; then determine what fraction this is of the volume of the wall section, V_{spot}, and multiply times ρ_0 to give ρ_i, the density of measurement i. Thus in equations

$$V_{\text{spot}} = 2 \cdot \varphi_{\text{spot}} \cdot \left(\frac{D^3}{24} - \frac{\left(D/2 - w \right)^3}{3} \right) \cdot \sin\left(\frac{\varphi_{\text{spot}}}{2} \right) \tag{7}$$

and

$$\rho_i = \left(1 - \frac{n \cdot V_{\text{void}}}{V_{\text{spot}}} \right) \cdot \rho_0 \ . \tag{8}$$

The individual ρ_i will lie clustered about an average density, $\langle \rho \rangle$, but also very close to the average shell density given by

$$\rho_{\text{shell}} = \left(1 - v_f \right) \cdot \rho_0 \ . \tag{9}$$

It's not exactly ρ_{shell} because we have only taken measurements about the waist of the capsule, and there are certainly some fluctuations (quite small) when comparing this band to the total capsule.

Results

In Figure 1 is plotted the dependence of the relative rms, ρ_{M}, on void diameter, d, for 3 values of the void fraction, v_f, and for a spot size, φ_{spot}, of 6 ° (~105 μm square). The power dependence on d is $1.50 \pm .01$ as expected. Note that for small voids (<0.5 μm in diameter) the void fraction can be quite large. More about this later.

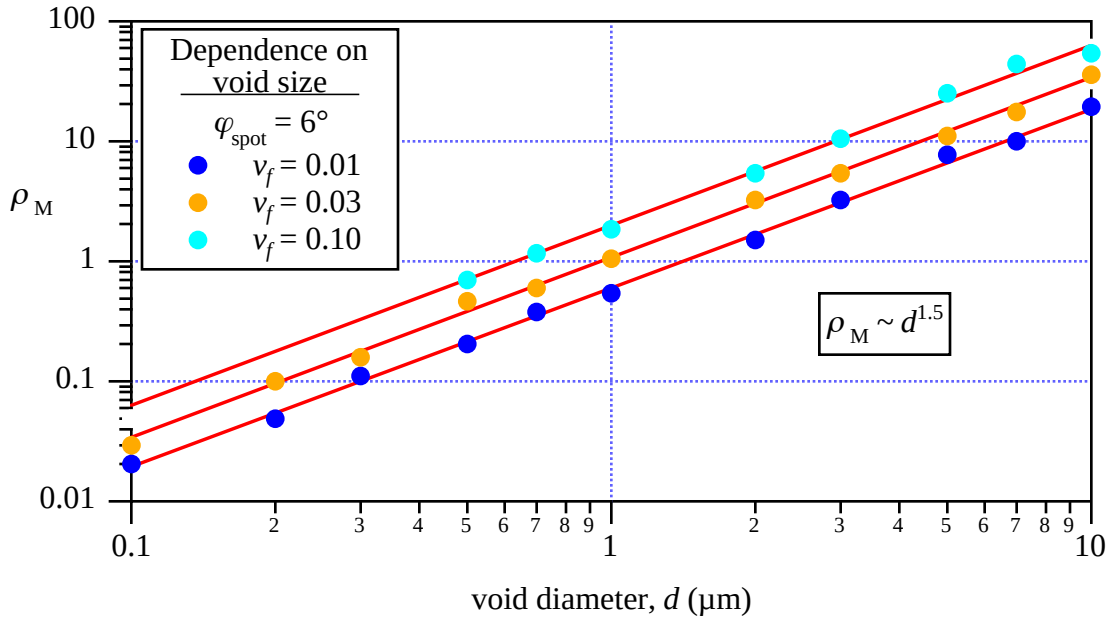

Figure 1. Dependence of ρ_{M} on void size.

In Figure 2 is a similar plot of as a function of void fraction, v_f, for several values of void diameter, d. The power dependence on v_f is 0.50 as expected. Note that even for a void fraction of 0.01 the size of acceptable voids is no more than 2 μm.

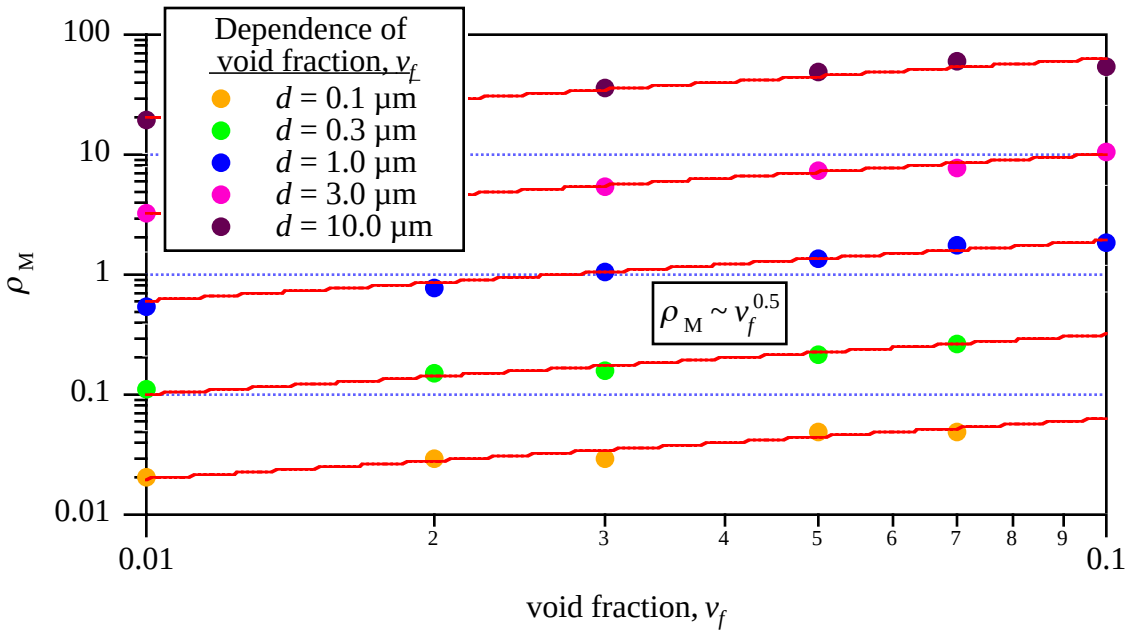

Figure 2. Dependence of ρ_M on void fraction.

The leading constant in eq 2 that depends upon spot size is all that is left to be determined. Actually this constant depends upon the volume of the shell sampled (V_{spot}, eq 7) which for small spots (small φ_{spot}) and constant shell size (D and w) goes as φ_{spot}^2 or the area of the spot, A_{spot}. The dependence of ρ_M on the area, A_{spot}, should go as $(1/A_{spot})^{1/2}$. This was checked by doing simulation with different spot sizes. Plotted in Figure 3 is ρ_M as a function of φ_{spot} for 3 combinations of v_f and d. The fitted red lines are $\rho_M = \text{const} / \varphi_{spot}$.

It is now useful perhaps to convert the φ_{spot} into a length, which we will call L, where clearly

$$L = \varphi_{spot} \cdot \frac{\pi D}{2\pi} = \varphi_{spot} \cdot \frac{D}{2} \tag{10}$$

(For a $\varphi_{spot} = 6° = 0.1047$ radians, $L = 104.7$ μm for $D = 2$ mm.) Thus eq 2 might be rewritten as

$$\rho_M = \frac{\text{const}}{L} \cdot v_f^{1/2} \cdot d^{3/2} \tag{11}$$

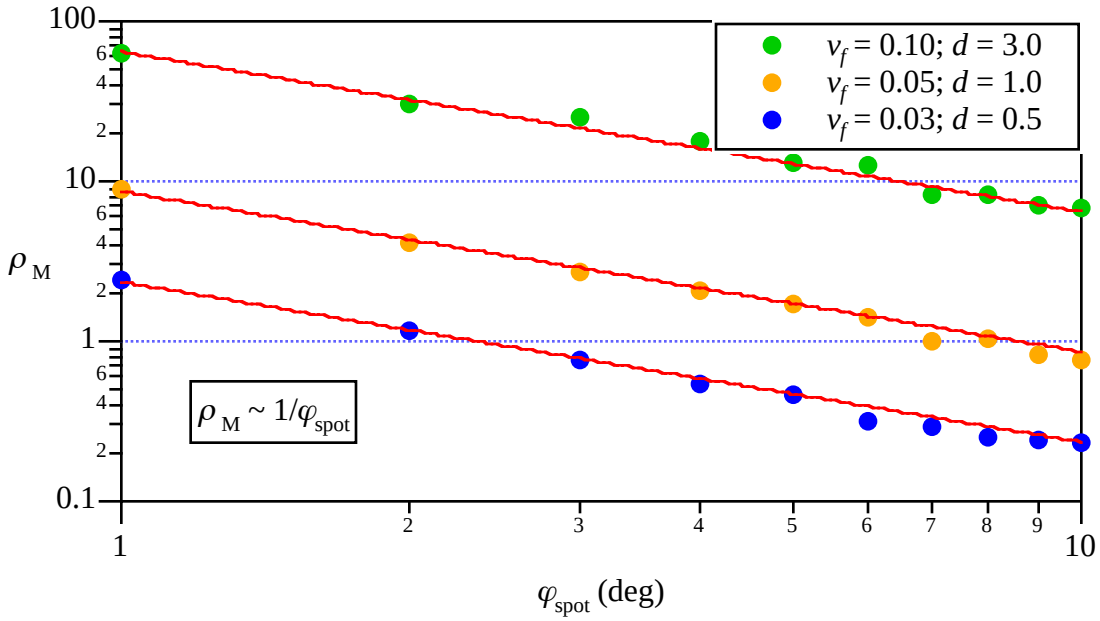

Figure 3. Plot of ρ_M as a function of the spot size showing an inverse relationship to the linear spot dimension, φ_{spot}. The fitted lines are of the form $\rho_M = \text{const} / \varphi_{spot}$.

Determination of the constant is simply accomplished by "fitting" all the simulation data (φ_{spot} = 3°, 6°, and 9°, v_f = 0.01 to 0.10, and d = 0.1 to 10.0 µm for D = 2000 µm and w = 162 µm) to eq 11. Basically

$$\text{const} = \frac{\rho_M \cdot L}{v_f^{1/2} \cdot d^{3/2}} \quad . \tag{12}$$

We will evaluate both L and d in µm, thus the units of the constant are $\mu m^{-1/2}$. In Figure 4 we show a scatter plot of this constant as a function of the various L, v_f, and d sets evaluated. The scatter, of course, is due to the variation in the simulation. But from this data a value for the constant of 635 $\mu m^{-1/2}$ can be determined (standard deviation of 55 $\mu m^{-1/2}$), thus eq 11 becomes

$$\rho_M = 635 \cdot \frac{v_f^{1/2} \cdot d^{3/2}}{L} \tag{13}$$

In Figure 5 we plot the values of d as a function of v_f that correspond to a ρ_M of unity (the 1 part in 10^4 spec) for L = 50, 100, and 200 µm. The Haan spec of a void fraction of 0.01 coupled with a 2.0 μm^3 void size (d = 1.56 µm for a sphere) is approximately consistent with the red curve. But what this plot makes clearer is the

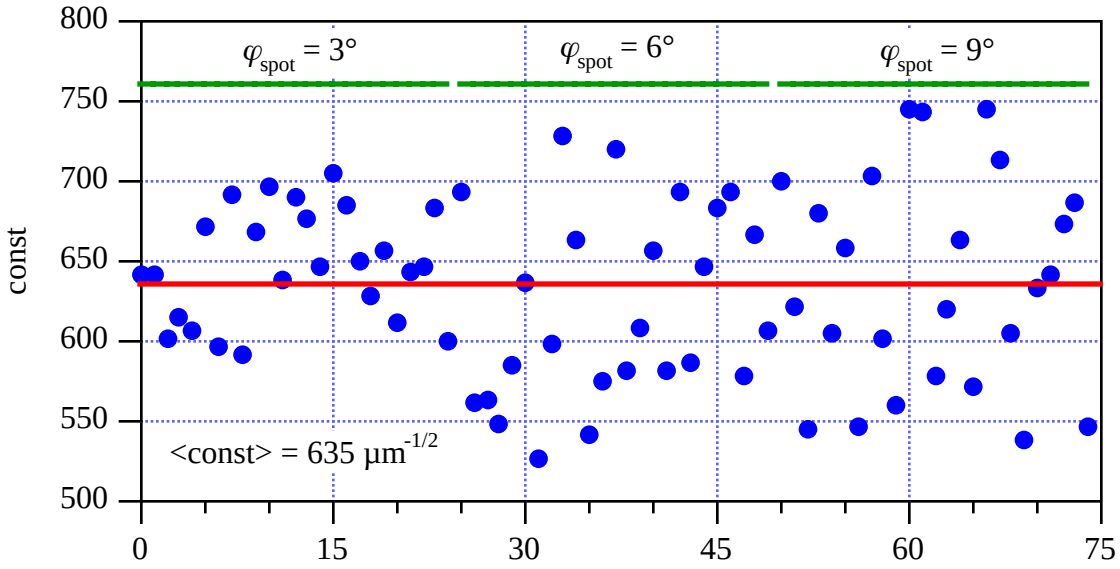

Figure 4. Scatter plot representation of data used to determine the proportionality constant in eq 11.

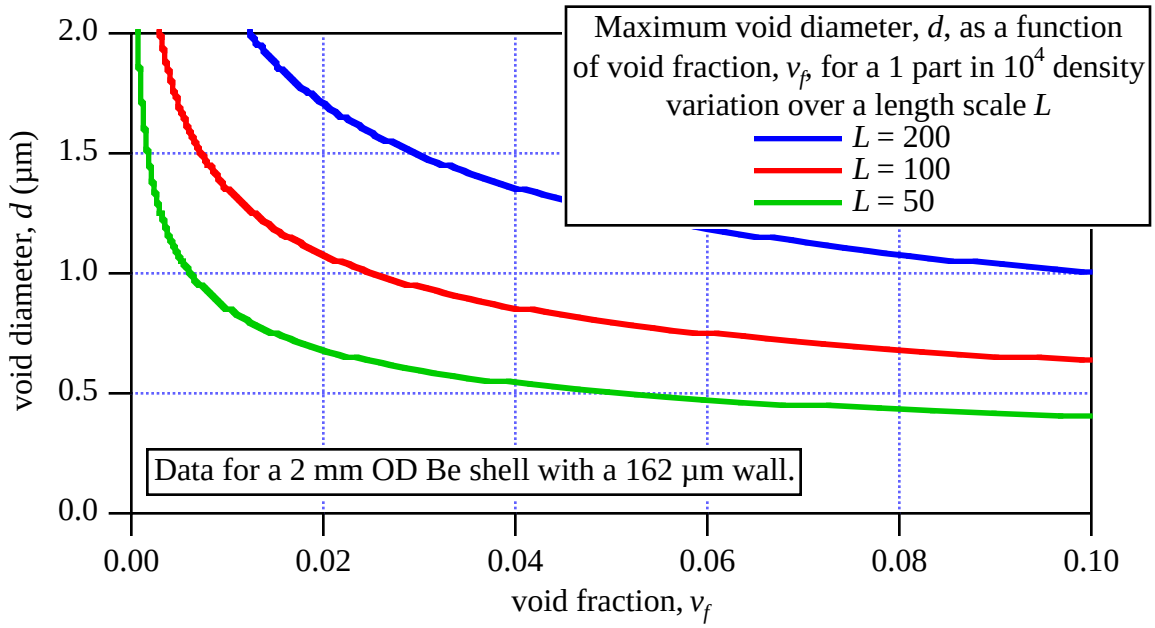

Figure 5. The values of d as a function of v_f that correspond to a ρ_M of unity (the 1 part in 10^4 spec) for L = 50, 100, and 200 μm.

"trade-off" between void fraction and void size. What is striking is that for a void diameter of 0.6 μm we can have a void fraction of 0.1 - the sample can be 10% underdense. In all but the worst samples the void size is less than 0.5 μm, more typically 0.2 μm.

However this view gives the entire opacity non-uniformity margin to voids. There may be other causes of opacity non-uniformity, and/or this is a place that we might tighten the specs. Thus in Figure 6 I plot additionally what the maximum void size should be for a spec of 1/2, 1/3, 1/4, 1/6, 1/10 of a part in 10^4, over a 100 μm length scale. This is equivalent to taking the Haan spec of $v_f \cdot V_{\text{void}} \le 0.02\ \mu\text{m}^3$ and reducing it by 2^2, 3^2, 4^2, 6^2, 10^2. Though certainly more restrictive, the requirement at 1/10 of a part in 10^4 is not unreasonable.

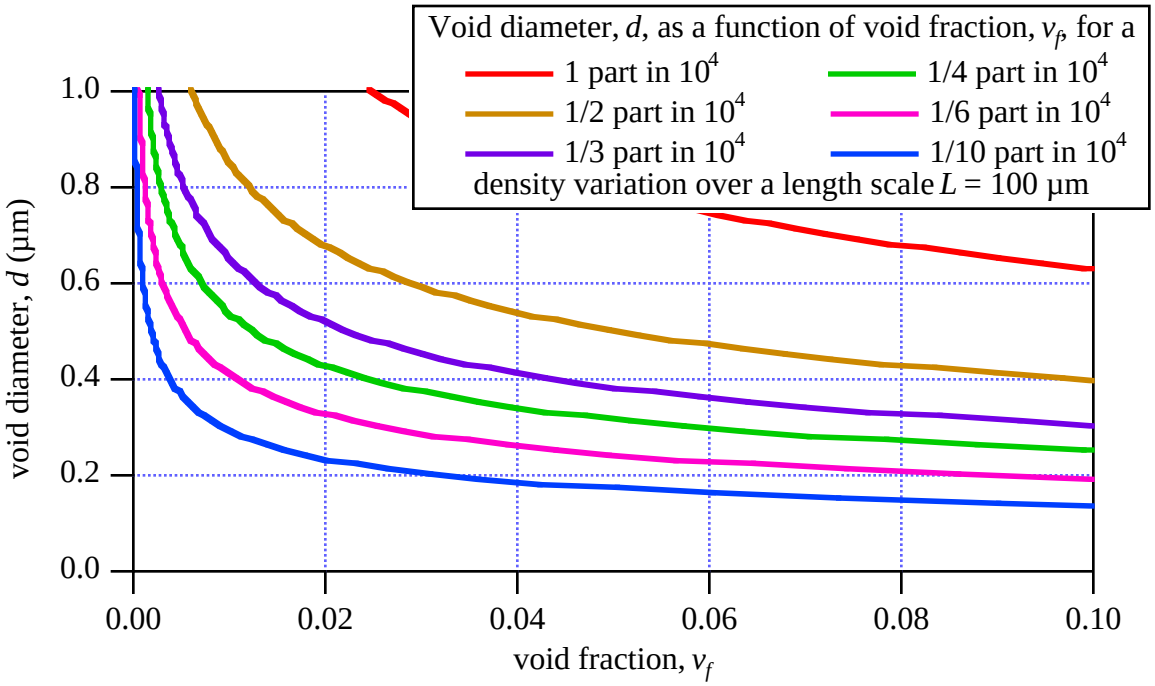

Figure 6. The values of d as a function of v_f that correspond to a ρ_{M} of 1, 1/2, 1/3, 1/4, 1/6, 1/10 for $L = 100\ \mu\text{m}$. This is equivalent to a reduction of the Haan spec ($v_f \cdot V_{\text{void}} \le 0.02\ \mu\text{m}^3$) by 2^2, 3^2, 4^2, 6^2, 10^2.

Some concluding caveats

First this model assumes a random placement of voids. This is probably not an unreasonable assumption; it is hard to think of any process that would result in a non-random placement, at least not angularly with correlation lengths of 100 μm. There could, however, be radial variations. These, however, would also be missed by the precision radiography measurement as well, and further are not as important to the implosion physics. Second, the precision radiography measurement by its nature will measure both walls at once, thus two wall thicknesses will be averaged. For this random void model that corresponds to a "length scale" of twice the spot size. Third, we have calculated the specification assuming all voids were of equal size. Clearly this is not the case. But if the largest voids we see fall below the size of interest, the remaining voids that make up the void fraction are even less important. Fourth, we have assumed spherical voids. What is important, for small random voids, is their net volume rather than their shape. Thus one must keep this in mind when looking at TEM pictures of voids, and try to evaluate them in terms of an "effective" spherical diameter.

Fifth, we have assumed that we either have a void or full density Be. It is certainly possible (perhaps likely) that intergrain regions are less than full density, but in a TEM we don't see a void. Density variations in this case can only be measured by Stephen's precision radiographic technique. Lastly, a word about density. There are implications (not good) for working with a lower effective density for Be due to the void fraction. Our experience at LLNL has been that the best density we have measured has about[3] a $v_f = .02$, but to date we have not been able to repeat this coating density. More typical are $v_f \approx .05$ (or larger). Our effort over the next few months will be to develop means to reduce the void fraction (and probably void size as well). But it may be unrealistic to expect that a $v_f \leq .01$ will be achieved, the implications of a design with $v_f = .05$ needs to be explored.

[3] Measurement of the shell density has an accuracy (at best) of 1-2%. Thus void fractions are approximate.